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EVALUATING NATECH RISKS IN THE LIQUID HYDROGEN MARITIME BUNKERING INFRASTRUCTURE

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ABSTRACT

The accelerating impacts of climate change are increasing the frequency and severity of natural hazards, intensifying risks associated with Natural Hazard-Triggered Technological Disasters (Natech). Concurrently, the global transition to low-carbon energy solution has positioned liquid hydrogen as an attractive alternative to conventional fuels, particularly for large-scale applications like maritime bunkering, due to its high energy density and minimal environmental footprint. However, liquid hydrogen bunkering facilities in coastal regions vulnerable to extreme weather events face significant Natech risks. Addressing these risks is essential for building resilient infrastructure and enhancing disaster preparedness. This study explores the application of inherent safety principles to investigate how the early integration of Natech considerations can improve the safety and resilience of the liquid hydrogen bunkering infrastructure. The findings aim to support stakeholders in implementing effective risk management strategies, fostering the safe and sustainable adoption of hydrogen use in maritime transport.

Keywords: Natech, inherent safety, disaster preparedness, liquid hydrogen, maritime bunkering

NOMENCLATURE

BOG	Boil-Off Gases
CFD	Computational Fluid Dynamics
CGH_2	Compressed Gaseous Hydrogen
DPI	Domino chain Potential Index
ERC	Emergency Release Coupling
ESD	Emergency Shut-Down
FBR	Full-Bore Rupture
FF	Flash Fire
H_2	Hydrogen
HHI	Human Inherent hazard Index
HPI	Human Potential hazard Index
JF	Jet Fire
LFL	Lower Flammability Limit
LH_2	Liquid Hydrogen
LNG	Liquified Natural Gas
MIMAH	Methodology for the Identification of Major Accident Hazards
Natech	Natural Hazard-Triggered Technological Disasters
PF	Pool Fire
STS	Ship-To-Ship
VCE	Vapor Cloud Explosion

1. INTRODUCTION

In the chemical and process industries, natural hazards can pose significant risks by impacting process and storage equipment, potentially triggering severe accidents. These accidents, referred to as Natech (Natural Hazard-Triggered Technological Disasters) scenarios, can lead to business interruptions and catastrophic outcomes, including damage to equipment, the release of hazardous substances, and subsequent toxic dispersions, fires, explosions, or environmental contamination [1].

Notably, the 2011 Tohoku tsunami, which caused significant damage to liquefied natural gas (LNG) pipelines at the Shin Minato terminal in Sendai City leading to the release of hazardous materials, stands as a critical example of such accidents [2]. Tsunamis, as well as earthquakes, floods and landslides, are classified as hydro-meteorological hazards, which have shown an increasing trend in the return period and intensity in recent years—a pattern anticipated to escalate further due to the impacts of climate change [3]. Consequently, the risks associated with Natech scenarios triggered by these events are projected to rise significantly in the near future [4].

Meanwhile, interest in liquid hydrogen (LH_2) as a low-carbon alternative fuel for maritime transport is rapidly growing, driven by its potential to support the global energy transition [5]. LH_2, in fact, with its high energy density by weight and zero-carbon emissions at the point of use, is being explored as a key solution to decarbonize the shipping industry, one of the largest contributors to global greenhouse gas emissions. However, its adoption hinges on the establishment of safe and efficient bunkering infrastructure [6].

Bunkering, the process of supplying fuel to ships, including the logistics of loading and distributing the fuel among accessible shipboard tanks, is a critical operation that must address the unique properties of LH_2 [7]. Its cryogenic temperature of -253 °C necessitates advanced insulation systems to prevent the generation of boil-off gases (BOG) and maintain stability during storage and transfer [6]. Additionally, hydrogen (H_2) embrittlement, leak risks, and flammability properties require stringent safety measures, including specialized leak detection systems, ventilation protocols, and emergency response plans [5].

While LH_2 bunkering technology offers a compelling solution to decarbonize the shipping industry, its infrastructure is vulnerable to Natech scenarios. In particular, extreme natural events such as tsunamis, floods, and storms pose significant risks to the integrity of LH_2 bunkering systems, potentially undermining their role in mitigating climate change. Therefore, as LH_2 adoption accelerates, it is crucial to evaluate the safety of its infrastructure against the growing threat of climate change-driven natural hazards. Despite the increasing awareness of Natech risks, most research has focused on chemical and process industries, leaving the specific vulnerabilities of H_2 systems underexplored [8]. The present study addresses this gap by developing a methodological framework to assess the Natech risks associated with LH_2 bunkering systems, particularly under tsunamis and wind-wave events. Through inherent safety principles, widely applied in the context of the Oil&Gas sector [9-11], the study evaluates how natural hazards can trigger equipment failures, amplify risks, and compromise safety, offering valuable insights for designing a more resilient LH_2 infrastructure capable to withstand these challenges.

In the following, Section 2 introduces the methodology adopted to assess the inherent safety indexes and Section 3 presents the application of the procedure to two different notional case studies. Then, the results are displayed and discussed in Section 4. Finally, some conclusive remarks are outlined in Section 5.

2. METHODOLOGY

The step-by-step methodology proposed in the current study, outlined in Figure 1, is designed to comprehensively assess the impacts posed by offshore extreme natural hazards, such as tsunamis, hurricanes, or wave storms, on bunkering infrastructure. By calculating inherent safety indexes, the methodology provides a preliminary assessment of damage escalation in Natech scenarios compared to that caused by typical failure mechanisms.

Step 1 of the methodology involves identifying reference natural hazards that may occur offshore in the bunkering area under assessment. This includes extreme natural events impacting both the waters within the port and those further offshore. In Step 2, a reference offshore natural hazard, among the ones identified in Step 1, is selected. Step 3 then characterizes this event in terms of intensity and frequency of occurrence. This characterization includes analyzing factors as the intesity measure (e.g., wind speed, seismic magnitude, or wave height) and the likelihood of occurrence ($f_{natural\ hazard}$), which can be determined through historical data or return periods [12].

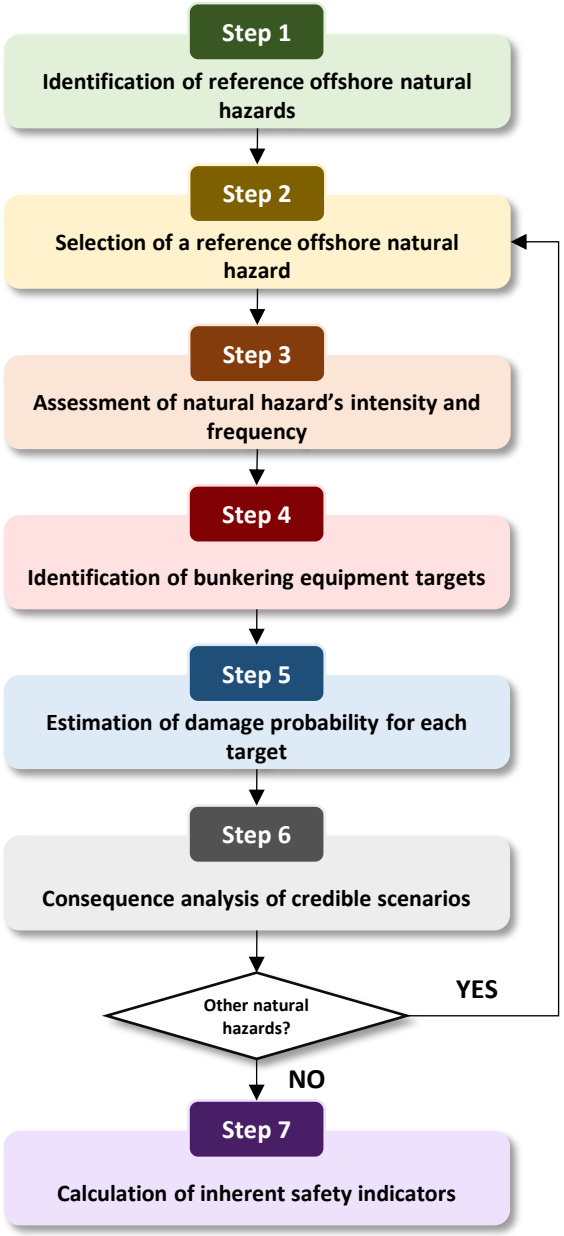

FIGURE 1: OVERVIEW OF THE METHODOLOGY.

In the current study, tsunamis and wave-wind events are considered as the reference natural hazards. Therefore, the return period and the impact vector—composed of two elements: maximum water speed and maximum wave height—are the parameters used to characterize the extreme natural event [13,14].

In Step 4, the focus shifts to identifying the most critical bunkering equipment items that could potentially be impacted by the selected reference natural events. These critical targets represent the hazardous equipment, such as pipes, storage tanks, or loading and unloading infrastructure, established by the criterion suggested in the MIMAH (Methodology for the Identification of Major Accident Hazards) procedure [15]. This criterion consists of an indexing approach, where the mass of the stored hazardous material is compared to a threshold quantity. The threshold is determined by the hazardous properties of the substance, its physical state, tendency to vaporize, and proximity to other hazardous equipment.

Subsequently, Steps 5 and 6 involve estimating the damage (failure) probability of each identified target using equipment vulnerability models and then evaluating specific damage distances adopting conventional consequence simulation models [16,17] and predefined damage threshold values [18]. The damage distance represents the maximum distance from the release location at which the physical effects of the scenario equal the assumed human threshold values.

After completing Step 6, the methodology includes a decision point to verify that all the reference natural hazards identified in Step 1 have been considered. If additional reference natural hazards need evaluation, the process returns to Step 2. Otherwise, it advances to Step 7 to calculate the safety indexes. This cyclical approach emphasizes continuous refinement and adaptation throughout the process, ensuring that new insights and potential modifications are incorporated as the analysis progresses.

Finally, Step 7 encompasses calculating three inherent safety indexes:

1. The Human Potential hazard Index (HPI), which takes into account the consequences of the worst-case scenario on human targets [18];
2. The Human Inherent hazard Index (HHI), which accounts for the frequency and consequences of the worst-case scenario on human targets [18];
3. The Domino chian Potential Index (DPI), which defines the area potentially affected by escalation (domino) effects [19], which may amplify the impact of an initial event by triggering a series of cascading accidents [20].

The first two indexes provide a preliminary quantification of risk to humans [18]. Specifically, HPI provides a rough estimation of the impacted area, while HHI incorporates the probability of equipment failure to estimate the impact of the worst credible accident scenario. HPI and HHI can be calculated for each k^{th} equipment item as follows:

$$HPI_k = \pi \cdot \left(\max_i \left(\max_j \left(\max\left(d_{i,j,k}, 5\ m\right) \right) \right) \right)^2 \quad (1)$$

$$HHI_k = \pi \cdot \sum_{i=1}^{n_k} f_k \cdot \left(\max_j \left(\max\left(d_{i,j,k}, 5\ m\right) \right) \right)^2 \quad (2)$$

where n_k represents the number of release modes considered for the k^{th} target, $d_{i,j,k}$ denotes the maximum damage distance of the j^{th} accident scenario associated with the i^{th} release mode of the k^{th} target, and f_k is the failure frequency of the k^{th} target calculated using the following formula:

$$f_k = \Psi_k \cdot f_{natural\ hazard} \quad (3)$$

where Ψ_k indicates the damage (failure) probability of the k^{th} target. The value of 5 m defines a "near field" zone illustrative of the area in which consequence models are deemed as unreliable [21].

The third index, DPI, provides a preliminary ranking of the hazard of the primary targets and can be calculated as follows:

$$DPI_k = \pi \cdot \max_i \left(\max_j \left(D_{h,i,j,k} \right) \right)^2 \quad (4)$$

where DPI_k represents the domino chain potential index for the k^{th} primary target, which is considered the initial item from which the cascading sequence occurs, and $D_{h,i,j,k}$ is the damage distance for the j^{th} accident scenario associated with the i^{th} release mode of the k^{th} target, with respect to a generic h^{th} equipment item, referred to as the secondary item located near the primary one [19]. Also in this case, the damage distance represents the maximum distance from the release location at which the physical effects of the scenario equal the assumed domino threshold values. This indicator does not require specific layout information, making it suitable for application during the early design phases, when detailed and site-specific lay-out data are not yet available.

3. CASE STUDIES

Two different case studies were considered for the application of the methodology, referred to as the coastal case study and the offshore case study. Both cases share the same bunkering infrastructure. However, they differ in the natural hazards accounted for.

The bunkering configuration analyzed in both cases is the ship-to-ship (STS) setup, as depicted in Figure 2 [22,23]. This configuration involves a receiving ship anchored to a bunker ship, which acts as a "mobile" fuel station. It allows for high bunker rates, large refueling capacities, and flexibility in locations. In fact, it can be performed either in port or outside port boundaries, depending primarily on the availability of shore-based infrastructure [24]. In this configuration, LH_2 is transferred through a flexible hose (red line in Figure 2) from the bunker vessel to the receiving vessel thanks to a pressure difference between the two tanks. Additionally, a flexible hose transferring compressed gaseous hydrogen (CGH_2) is

implemented (blue line in Figure 2) as a precaution to address BOG generation [10]. However, since BOG can generally be avoided, this hose is not considered a critical equipment item for the safety analysis. Therefore, the equipment items identified as critical targets through the methodology are the bunker vessel, the receiving vessel, and the LH_2 flexible hose.

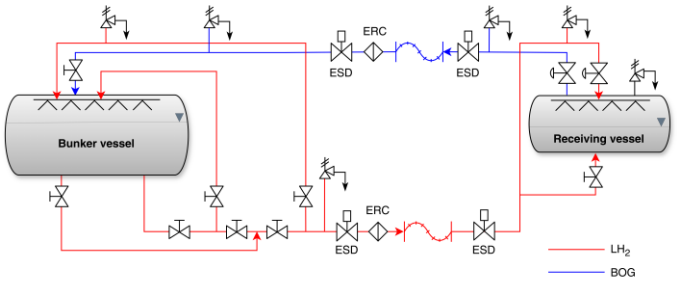

FIGURE 2: STS LH_2 BUNKERING INFRASTRUCTURE (ESD: EMERGENCY SHUT-DOWN, ERC: EMERGENCY RELEASE COUPLING).

A summary of the features of this equipment is provided in Table 1.

TABLE 1: MAIN DESIGN CHARACTERISTICS OF THE TARGET EQUIPMENT CONSIDERED IN THE CASE STUDIES.

Feature	Bunker vessel	Receiving vessel	LH_2 flexible hose
Diameter (m)	16	8	0.32
Length (m)	39	20	20
Volume (m^3)	9986	1248	-
Pressure (bara)	6	2	4
Filling level (%)	85	85	-

The coastal case study assumes that the bunkering system is located at the port and considers tsunamis as the primary natural hazard. In contrast, the offshore case study assumes that the facility is situated far from the coast and evaluates wind-wave events as the natural hazard of concern. Table 2 collects the parameters describing the reference natural events assumed for the two case studies.

TABLE 2: NATURAL EVENTS CONSIDERED FOR THE CASE STUDIES.

Reference code	Return period (y)	Wave height (m)	Water speed (m/s)
Coastal case study – tsunami			
T1	500	0.2	0.25
T2	5000	1.2	0.75
Offshore case study – wind-wave event			
W1	500	2.05	6.56
W2	300	1.05	3.76

Data on tsunamis were sourced from Lorito et al. [13], while data on wind-wave events were retrieved from Laface and Arena [25], incorporating friction factors for moderate-calm sea conditions [26]. These factors enable the translation of wind speed into water speed for such events. In these case studies, the frequency of occurrence of the natural hazard, indicated as $f_{natural\ hazard}$ in Eq. (3), is calculated as the inverse of the return period.

Based on this, in order to estimate the failure frequency of a specific equipment target with respct to a natural hazard (refer to f in Eq. (3)), it is necessary to determine the damage probabilities (Ψ in Eq. (3)) using equipment vulnerability models for floods. In this study, models from Landucci et al. [27] are applied for horizontal pressurized storage tanks (bunker and receiving vessels), while models from Rossi et al. [28] are used for pipelines (LH_2 flexible hose). These models require input data concerning flooding conditions, geometric and operating parameters of equipment framework and storage system, and assuming a filling level distribution. In the case studies carried out, a linear distribution of possible filling levels between Φ_{min} (1%) and Φ_{max} (90%) was assumed for the calculation of Ψ. More detailed information on equipment failure resulting from floods are reported elsewhere [29,30].

The consequence analysis then requires input data concerning the reference release modes and end-point scenarios. In the case of pressurized vessels, flooding may cause vessel displacement, but vessel rupture due the external pressure or wave impact is not credible due to the double-wall vacuum-insulated tanks designed for cryogenic substances at high pressure [31]. As such, the severe release modes selected for this study—aligned with equipment vulnerability models for floods and having failure frequencies obtained using Eq. (3)—include:

- V_R1: the release of the entire content of the vessel considering a full-bore rupture (FBR) of pipe connections;
- V_R2: the release of the entire inventory within 10 min.

On the contrary, in the case of the LH_2 flexible hose, release modes from the indication provided by the IOGP (*International Association of Oil & Gas Producers*) [32] were considered by drawing parallels with LNG facilities. The critical release modes identified are:

- P_R1: the FBR of the flexible hose;
- P_R2: the release from a hole with an effective diameter equal to 10% of the flexible hose diameter, up to a maximum of 50 mm.

These release modes, when applied to equipment handling cryogenic LH_2—a flammable and explosive substance [8,9]—result in four potential end-point scenarios [15,16]: flash fire (FF), jet fire (JF), pool fire (PF), and vapour cloud explosion (VCE), indicated in the first column of Table 3. Against the human target, these scenarios can generate, as physical effects, transient or stationary radiation and overpressure (see the second column of Table 3). Due to the properties of LH_2, the safety assessment excludes scenarios involving chemical interactions between the released substance and floodwaters. The entity of the physical effects associated with the end-point scenarios (i.e.,

the damage distances) were evaluated using PHAST 8.71 software [33], according to conventional procedures [16,17] and considering specific human and domino threshold values [18,19] as indicated in the fourth and fifth column of Table 3.

TABLE 3: END-POINT SCENARIOS WITH ASSOCIATED PHYSICAL EFFECTS AND HUMAN AND DOMINO THRESHOLD VALUES CONSIDERED FOR THE CASE STUDIES.

End-point scenario	Physical effect	Human threshold value		Domino threshold value[b]
		1° level	2° level	
Flash Fire (FF)	Transient radiation	½ LFL[a]	LFL[a]	-
Jet Fire (JF)	Stationary radiation	7.0 kW/m^2	12.5 kW/m^2	50.0 kW/m^2
Pool Fire (PF)	Stationary radiation	7.0 kW/m^2	12.5 kW/m^2	50.0 kW/m^2
Vapor Cloud Explosion (VCE)	Overpressure	0.14 bara	0.30 bara	0.16 bara

[a] LFL, lower flammability limit (ppm), equal to 40,000 ppm [34].
[b] For pressurized secondary equipment [19].

It is important to highlight that PHAST 8.71 software, which relies on integral models to assess the impacts of critical events, does not account for site-specific characteristics that can significantly influence phenomena such as dispersions and flash fires in the coastal case study. Elements like the geometry of the terminal, the presence of obstacles, and complex terrain features play a crucial role in shaping these events. To accurately capture such effects, the use of Computational Fluid Dynamics (CFD) simulations would be required [35].

The environmental conditions assumed for the modelling of the consequences are reported in Table 4.

TABLE 4: ENVIRONMENTAL CONDITIONS ASSUMED FOR THE CONSEQUENCE ANALYSIS.

Parameter	Value	Unit
Wind velocity	1.5	m/s
Pasquill class	F	-
Relative humidity	70	%
Ambient temperature	10	°C
Surface roughness length	0.2	mm

For the sake of comparison, an inherent safety evaluation was also carried out for the conventional scenarios caused by internal failures. This allows to better investigate the risk indexes before and after the incorporation of Natech scenarios [9]. In this case, the failure frequencies assigned to the release modes (V_R1, V_R2, P_R1, P_R2) are derived from baseline data available for standard components [32,36,37].

4. RESULTS AND DISCUSSION

In the present Section, the key results obtained applying the novel methodology developed are illustrated and discussed. In particular, the adoption of vulnerability models for floods enabled the determination of specific failure frequencies for the three critical equipment targets identified, as shown in Figure 3.

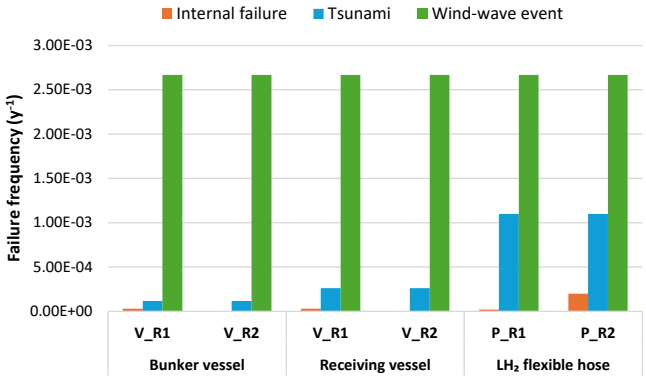

FIGURE 3: FAILURE FREQUENCIES DUE TO INTERNAL AND NATURAL CAUSES FOR THE CRITICAL TARGETS CONSIDERING THE RELEASE MODES DEFINED IN SECTION 3.

Basically, all equipment experienced failures due to both internal damage events and natural hazards across the evaluated reference release modes. However, wind-wave events were found to be the most significant cause of failure, with failure frequencies up to three orders of magnitude higher than those associated with internal failures. Tsunamis, on the other hand, resulted in failure frequencies up to two orders of magnitude higher than those related to internal failures. Among the critical equipment targets, the LH_2 flexible hose exhibited the highest failure frequencies across all reference release modes. Internal damage demonstrated the greatest impact on the LH_2 flexible hose in the case of a small leak (i.e., reference release mode P_R2).

Regarding damage distances related to human targets for different release modes characterizing the critical equipment items, the results are shown in Figure 4. As expected, the damage distances corresponding to first-level human thresholds are greater than those associated with second-level thresholds, as the first-level thresholds represent less severe damage conditions. Among the end-point scenarios, flash fires posed the greatest risk, with damage distances reaching up to 1 km when involving the bunker vessel. The flash fire was also the most severe end-point scenario for the receiving vessel, with damage distances extending up to 330 m. However, for the LH_2 flexible hose, the worst consequences were associated with the jet fire and vapor cloud explosion, both resulting in damage distances as high as 110 m.

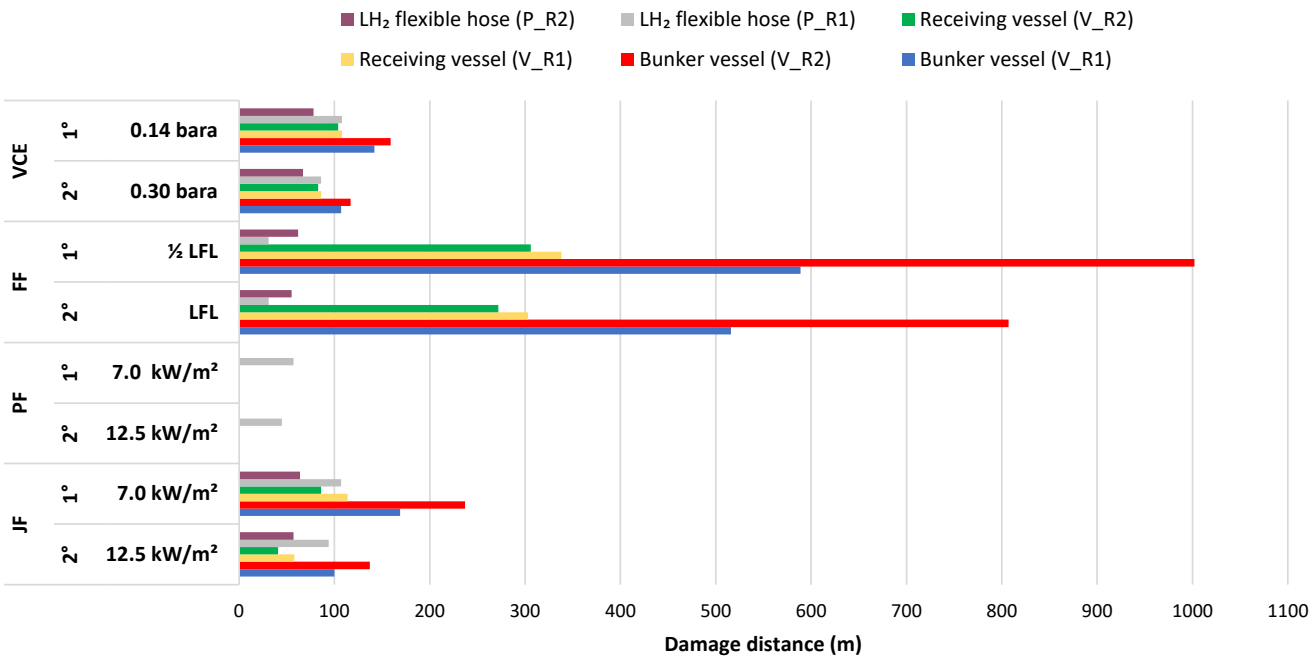

FIGURE 4: DAMAGE DISTANCES RELATED TO THE FIRST- AND SECOND-LEVEL HUMAN THRESHOLD VALUES (SEE TABLE 3) FOR THE CRITICAL TARGETS AND THEIR SPECIFIC REFERENCE RELEASE MODES.

Clearly enough, the bunker vessel, being the critical equipment with the highest pressure and volume, accounted for the largest damage distances across all considered end-point scenarios.

Notably, the pool fire scenario occurred only when FBR affected the LH_2 flexible hose, with resulting damage distances of approximately 58 m.

Since the case studies differ only in the type of natural event affecting them, and the HPI is independent of the cause of failure, the HPI values were the same for both case studies. Based on Figure 4, the maximum damage distance was selected to calculate the maximum impacted area for the worst-case end-point scenario affecting the bunkering system. Consequently, the HPI values were determined to be 3.5×10^6 m^2 and 2.4×10^6 m^2 for the first- and second-level human threshold values, respectively, as shown in Figure 5.

Conversely, the HHI, accounting for failure frequencies, differed between the coastal and offshore case studies, as shown in Figure 6. Indeed, the HHI is influenced by both conventional and Natech contributions. Specifically, Natech accidents significantly increase the inherent hazard indexes, with wind-wave events having a greater impact than tsunamis. In fact, wind-wave events have shorter return periods and thus higher frequencies of occurrence, further increasing the final HHI values.

Regardless of the damage threshold level, tsunamis raised the conventional HHI by approximately 20 times, while wind-wave events increased it by about 200 times. Therefore, bunkering systems located outside the port should implement much more robust solutions to face Natech accidents compared to systems located in ports, where the effects of tsunamis are comparatively less severe although non-negligible when compared to the conventional case.

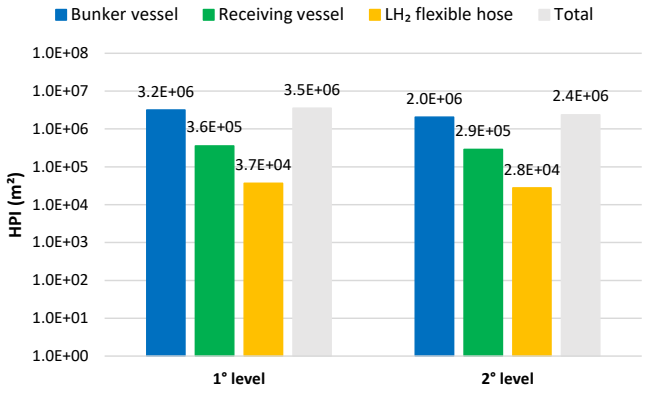

FIGURE 5: HUMAN POTENTIAL HAZARD INDEX (HPI) CALCULATED IN CORRESPONDENCE WITH THE FIRST- AND SECOND-LEVEL HUMAN THRESHOLD VALUES (SEE TABLE 3) FOR THE CRITICAL TARGETS.

Lastly, the graph in Figure 7 depicts the DPI values calculated for the identified critical equipment targets based on the specified domino threshold values reported in Table 3. All the critical targets showed DPI values within the same order of magnitude. However, the bunker vessel demonstrated the highest DPI value, approximately 7×10^4 m^2, followed by the receiving vessel with a DPI value of approximately 3.3×10^4 m^2. The LH_2 flexible hose presented the lowest DPI value, around 3.1×10^4 m^2. These differences highlight the varying levels of escalation hazard among the three equipment items. The bunker vessel was

identified as the more critical unit; thus, the design of this target should be carefully examined both with respect to layout definition (e.g., providing high separation distances) and to limit the probability of failure and the magnitude of actual consequences of loss of containment (e.g., reducing the inventory, adopting passive protections, improved leak detection systems, etc.).

Overall, these findings highlight the importance of considering natural hazards as potential causes of equipment failure in bunkering facilities.

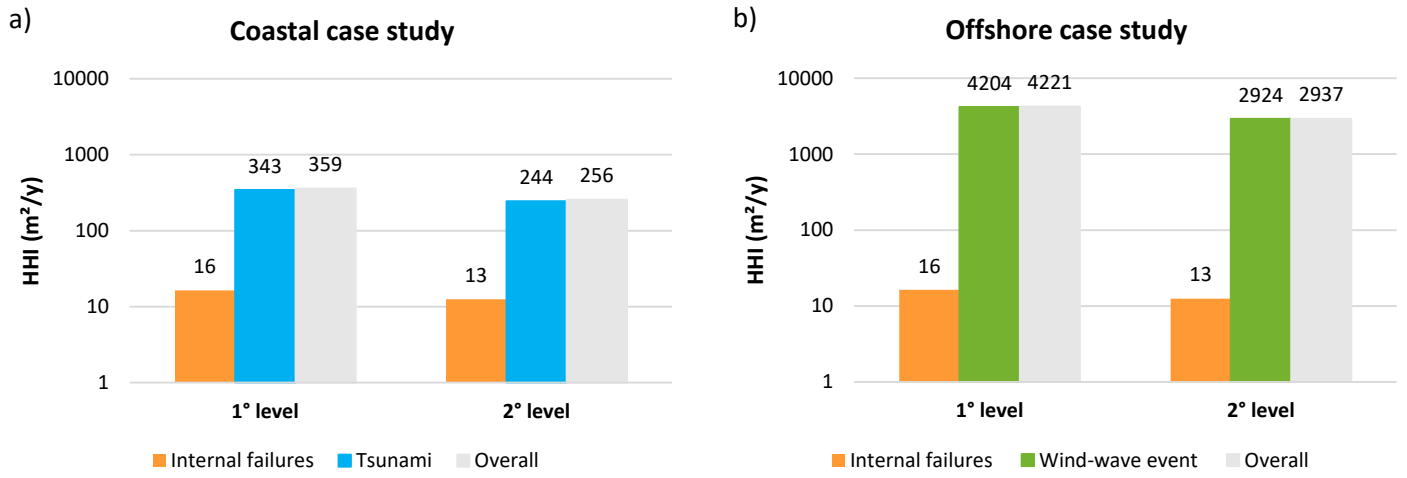

FIGURE 6: HUMAN INHERENT HAZARD INDEX (HHI) CALCULATED IN CORRESPONDENCE WITH THE FIRST- AND SECOND-LEVEL HUMAN THRESHOLD VALUES (SEE TABLE 3) FOR A) THE COASTAL CASE STUDY AND B) THE OFFSHORE CASE STUDY.

5. CONCLUSIONS

The current paper explored Natech risks in LH_2 maritime bunkering infrastructure, emphasizing the importance of integrating inherent safety principles to account for these risks in the early design stages. A step-by-step methodology was proposed to evaluate the impacts of natural hazards such as tsunamis and wind-wave events on critical equipment to obtain a preliminary assessment of risk. This involved identifying and characterizing reference natural hazards, estimating equipment failure probabilities by means of vulnerability models, and finally calculating human safety indexes based on a consequence-based approach.

The methodology was applied to a ship-to-ship bunkering configuration, considering both vessels and LH_2 flexible pipes as critical equipment items. Two different locations for bunkering were also evaluated, accounting for the refueling either in port or outside port boundaries.

Findings reveal that natural hazards significantly heighten failure probabilities for critical equipment. Wind-wave events, with their associated higher failure frequencies, pose greater risks than tsunamis, making offshore systems especially vulnerable. Natech scenarios were shown to increase inherent hazard indexes by up to 200 times, underscoring the critical need for robust safety measures in both coastal and offshore systems.

The results also emphasize the importance of developing advanced risk mitigation strategies to address the growing threat of natural hazard-triggered failures.

Future perspectives should include implementing more resilient infrastructure designs, enhancing early warning systems, and integrating real-time monitoring technologies. Furthermore, fostering collaboration among stakeholders to establish stringent safety standards and robust emergency response plans will be vital for ensuring the safe and sustainable deployment of LH_2 bunkering infrastructure. By prioritizing these measures, the maritime industry can better support the global energy transition while minimizing risks associated with Natech scenarios.

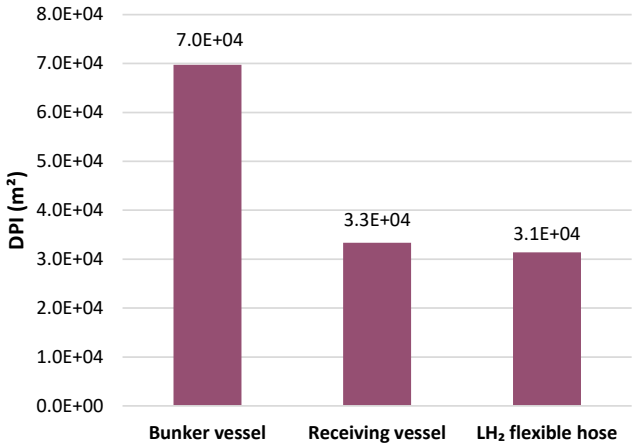

FIGURE 7: DOMINO CHAIN POTENTIAL INDEX (DPI) CALCULATED IN CORRESPONDENCE WITH THE DOMINO THRESHOLD VALUES (SEE TABLE 3) FOR THE CRITICAL TARGETS.

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